REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
06/18/2013	Interim Research Performance Report	02/01/2013 - 4/30/2013

4. TITLE AND SUBTITLE
Interim Research Performance Report
Quarterly Report No. 7

5a. CONTRACT NUMBER

5b. GRANT NUMBER
N00014-11-10752

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Nathan E. Murray, Charles E. Tinnet (U. of Texas at Austin), Brian S. Thurow (Auburn University), Praveen Panickar (CRAFT Tech.)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
The University of Mississippi
Jamie Whitten National Center
for Physical Acoustics
University, MS 38677

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Joseph Doychak
Office of Naval Research
875 North Randolph Street
Arlington, VA 22203-1995

10. SPONSOR/MONITOR'S ACRONYM(S)
ONR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The attached is a hard copy of the annual peer review presentation. Per the TM, this presentation fulfills the requirement for the quarterly report.

15. SUBJECT TERMS
Jet Noise Reduction, High Dynamic Range PIV, Computational Phased Array Beamforming, Aeroacoustics

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**		19	Nathan E. Murray
					19b. TELEPHONE NUMBER *(include area code)* 662-915-3190

20130705000

Toward Active Control of Noise from Hot Supersonic Jets

2013 ONR JNR BRC Annual Review

Contract: N00014-11-1-0752
Contract Monitor: Brenda Henderson
Office of Naval Research
Arlington, VA 22203-1995

Nathan E. Murray (PI)
Jamie Whitten National Center for Physical Acoustics (NCPA)
The University of Mississippi
University, MS 38677
(662) 915-3190
nmurray@olemiss.edu

Charles E. Tinney (Co-PI) – The University of Texas at Austin
Brian S. Thurow (Co-PI) – Auburn University
Praveen Panickar – Combustion Research and Flow Technology, Inc.

18 June 2013

Overview & Objectives

GOAL: Enhance the understanding of the effect that near-nozzle and inner-nozzle flow conditions have on jet noise radiation.

OBJECTIVE 1 – High-Fidelity Characterization of a Heated, Over-Expanded Supersonic Jet.

OBJECTIVE 2 – Source Identification Through Development of Advanced Analytical Diagnostics.

OBJECTIVE 3 – Enhanced Computational Modeling of Hot Supersonic Jets.

Achievements

Objective 1 – High-Fidelity Characterization

- Successful Acquisition of MHz-PIV Synchronized with Near- and Far-Field Acoustic Data
  - Ensembles of 16 Single-Exposure Images with 1 μs Time Resolution
- Detailed Jet Characterization through Additional Measurements
  - Probe Mapping of Pressure Distribution in the Plume
  - Acoustic Data versus Jet Operating Condition
  - Schlieren Flow Visualization
  - Pulse-Burst Laser Flow Visualization

Demonstration of Volumetric PIV with Plenoptic Imaging

STATUS:

- Data Reduction of Synchronous Data Set in Progress
  - PIV Image Processing
  - Streak Image Processing
  - Acoustic Data Reduction

Achievements

Objective 2 – Source Identification Diagnostics

- Developed "Shock Detection Algorithm"
  - For application to the pressure signal emitted by supersonic jets.
  - Enhanced understanding of potential sources for crackle.
  - Enhanced understanding of cumulative non-linear distortion – specifically the implications for range restricted environments (lab scale).
- Developed Analysis Methodologies to Investigate Noise Source Terms
  - Application to LES data shows preliminary results that wavenumber/frequency content shows consistency along lines of constant convection velocity.
  - Structured with the goal of application to the synchronous data set.

Achievements

Objective 3 – Enhanced Computational Modeling

- Enhanced Hybrid RANS/LES Methodology to Include Inner-Nozzle Features in the Jet Simulation
- Developed and Exercised a Computational Framework for Phased Array Analysis
  - *Also applicable to Objective 2.*

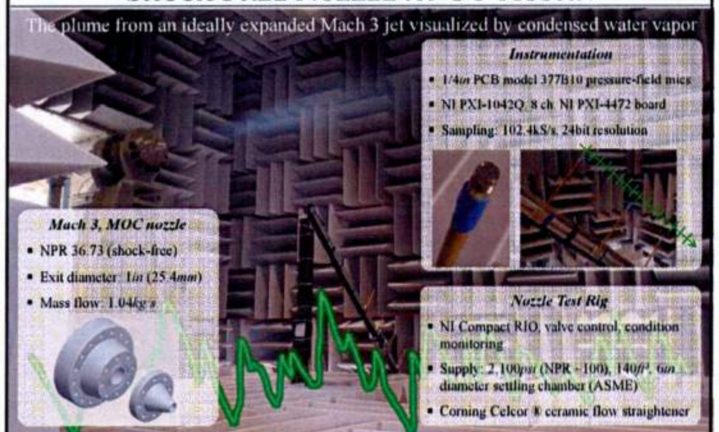
Outline of Discussion

- Brief discussion of the jet facilities and characteristics:
  - Shock Free Nozzle at UT-Austin
  - Conic-Section Nozzle at U. Mississippi
- What we learned about Mach wave emission and crackle…
- How we improved Hybrid RANS/LES modeling for military style nozzles…
- What we found from the computational phased array analysis…
- What we have learned by investigating noise source terms with LES data…
- How we setup and acquired the synchronous data set…
  - Preliminary results of streak-image analysis.
  - Preliminary results from Time-Resolved PIV analysis.
- Another promising approach… Plenoptic PIV

Outline of Discussion

- Brief discussion of the jet facilities and characteristics:
  - Shock Free Nozzle at UT-Austin
  - Conic-Section Nozzle at U. Mississippi
- What we learned about Mach wave emission and crackle…
- How we improved Hybrid RANS/LES modeling for military style nozzles…
- What we found from the computational phased array analysis…
- What we have learned by investigating noise source terms with LES data…
- How we setup and acquired the synchronous data set…
  - Preliminary results of streak-image analysis.
  - Preliminary results from Time-Resolved PIV analysis.
- Another promising approach… Plenoptic PIV

Shock Free Nozzle at UT-Austin

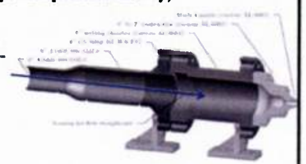


SHOCK FREE NOZZLE AT UT-AUSTIN

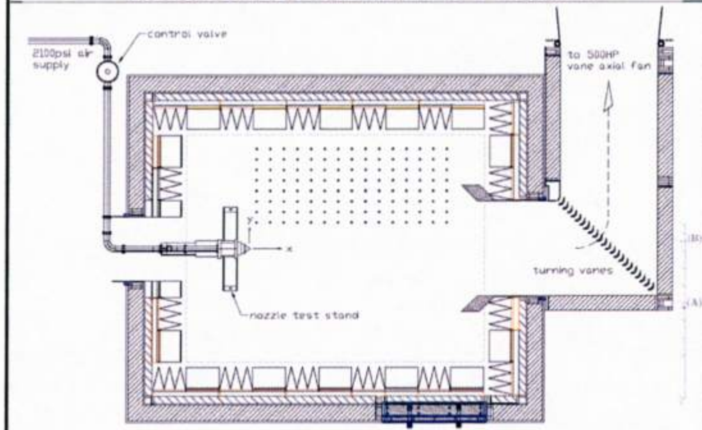
Experimental conditions (estimated from quasi 1-D isentropic compressible flow eq.)

- Current data: acquired during 3 days (Fall 2011)

		grid-array *(day 1)*	grid-array *(day 2)*
measured	M_j		$3.00 \pm 1\%$
	$NPR = p_0/p_\infty$		$36.73 \pm 4.5\%$
	p_∞ $[kPa]$	100.7	100.8
	T_0 $[K]$	291.2	286.2
	T_∞ $[K]$	293.3	287.2
	RH $[\%]$	75.4	63.2
calculated	T_j $[K]$	104.0	102.2
	a_j $[m/s]$	204.4	202.7
	a_∞ $[m/s]$	343.3	339.7
	U_j $[m/s]$	613.3	608.0
	$f_c = U_j/D_j$ $[kHz]$	24.1	23.9
	T_j/T_∞	0.35	0.36
	ρ_∞/ρ_j	0.35	0.36
	Re_j	$7.4 \cdot 10^6$	$7.6 \cdot 10^6$
	$U_c = 0.80U_j$ $[m/s]$	$\boxed{490.6}$	486.4
	$M_a = U_j/a_\infty$	$\boxed{1.79}$	1.79
	$M_c = U_c/a_\infty$	$\boxed{1.43}$	1.43
	ϕ $[degr]$	$\boxed{45.6}$	45.7



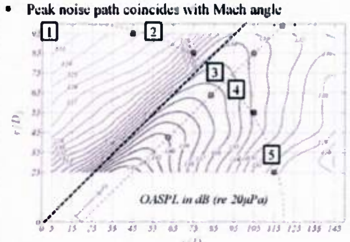
SHOCK FREE NOZZLE AT UT-AUSTIN



SHOCK FREE NOZZLE AT UT-AUSTIN

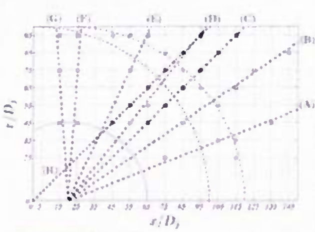
Spatial topography of OASPL

- Classical heart shape pattern and cone of silence
- Peak noise path coincides with Mach angle



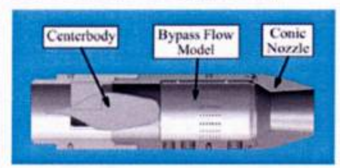
Attention to the "far-field" of the jet

- Non-linear metrics.
    - Skew of p and p'
    - Kurtosis of p and p'
    - Morfey-Howell indicator
    - Gol'dberg number
    - Burgers' equation
- Cumulative nonlinear distortion?

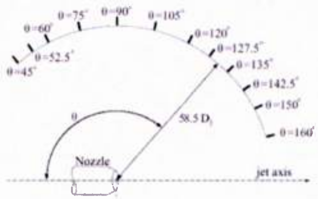


U. MISS. ANECHOIC JET LABORATORY

- 5 lbm/sec Continuous Flow Rate
- Propane Fired, Single-Lobe Burner
- Operation to 300 psi at 1500 °F
- Integrated pH-Balanced Alumina Seeding System
- 19-by-20-by-8 Feet Between the Wedge Tips
- Anechoic Above 120 Hz
- 1 ft/s Aspiration Maintains ≈ 90°F during Continuous Operation

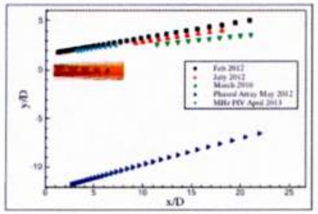


U. Miss. Anechoic Jet Laboratory



Far-Field Arc Array Microphones

- B&K Type 4939 1/4-inch
  - Free-field Microphones
- Type 2670 Pre-Amplifiers
- Curved Rail Support for Ease in Positioning



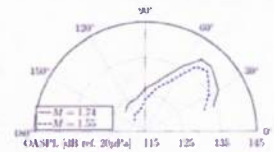
Near-Field Microphone Positions

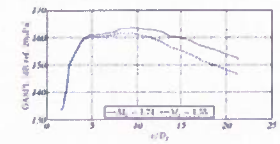
- Kulite Sensors:
  - Model XT-140-100A Transducers
  - 2.6 mm diameter, 100 psi range
- PCB Sensors:
  - Model 112A22 Accelerometer Compensated Pressure Probe
  - 50 psi range, Quartz Sensing Element

U. Miss. Anechoic Jet Laboratory

Summary of Test Conditions Considered

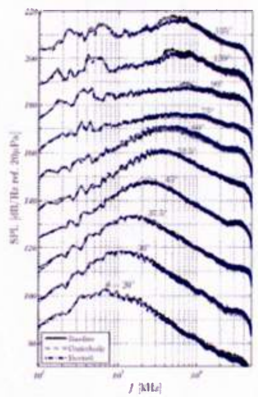
- Jet Nozzle
  - Conic Section Converging-Diverging Nozzle: Design Mach, $M_d = 1.74$.
  - Exit Diameter, $D_j = 50.8$ mm
- Pressure Matched Operation
  - $NPR = 5.2$, $TTR = 3.37$, $\gamma = 1.372$, $M_j = 1.74$, $M_a = 2.54$
- Over-Expanded Operation
  - $NPR = 3.9$, $TTR = 3.37$, $\gamma = 1.368$, $M_j = 1.55$, $M_a = 2.35$

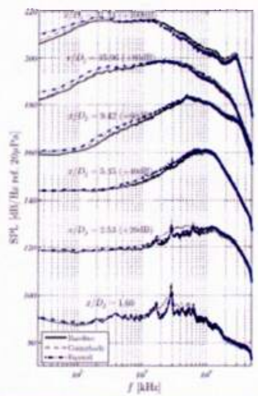




U. Miss. Anechoic Jet Laboratory

Basic Acoustic Characteristics – Pressure Matched





Outline of Discussion

- Brief discussion of the jet facilities and characteristics:
  - Shock Free Nozzle at UT-Austin
  - Conic-Section Nozzle at U. Mississippi
- **What we learned about Mach wave emission and crackle…**
- How we improved Hybrid RANS/LES modeling for military style nozzles…
- What we found from the computational phased array analysis…
- What we have learned by investigating noise source terms with LES data…
- How we setup and acquired the synchronous data set…
  - Preliminary results of streak-image analysis.
  - Preliminary results from Time-Resolved PIV analysis.
- Another promising approach… Plenoptic PIV

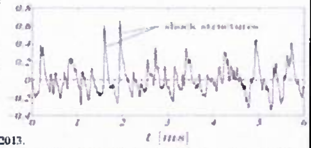
Mach Wave Emission and Crackle

Challenges

- Crackling and non-crackling signal have indistinguishable spectral content
- No unique measure of crackle – PDF based
  - Skewness of the pressure, Ffowcs Williams *et al.* 1975: S(p) > 0.4, S(p) < 0.3
  - Skewness of the pressure derivative, McInerny 1996, Gee *et al.* 2007
  - Kurtosis

Objectives

- Isolate and study the shock content in the waveform
- Investigate spatial and temporal patterns of crackle
- Revisit the metrics for the perception of crackle.
- *requires a robust shock detection algorithm!



[1] Baars, "*Acoustics from high speed jets with crackle*," PhD Dissertation May 2013.
[2] Baars & Tinney, "*Quantifying crackle inducing acoustic shock-structures emitted by a fully expanded Mach 3 jet*," AIAA Paper 2013-2081

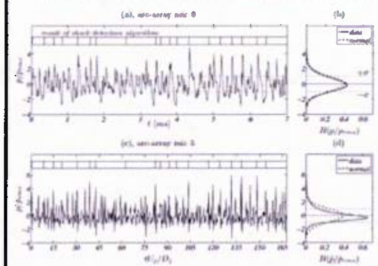
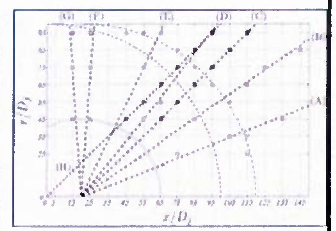
Shock Quantification

Shock Detection Algorithm (SDA)

- 1. pressure gradient: $T_p = 3\cdot 10^{-8}\sigma/(\delta dt)$
- 2. user-defined threshold: $T_p = 2.7\sigma$
- 3. median time of p⁺ and p⁻: $t_s = 0$

shock rise time: $\Delta t_s = 10^{-8}T_p/T_p$ = [illegible] ms
shock thickness: $\Delta x_s = 10^{-8}T_p/T_p u_\infty$ = [illegible]

- Time-preserving waveform analysis (wavelet based) to study spectral properties

Shock Quantification

Wavelet Transform

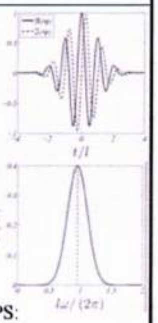
- Progressive, complex-valued, Morlet wavelet:

$$\psi(t/l) = e^{j\omega_\psi t/l} e^{-|t/l|^2/2} \qquad |\omega_\psi| = 6$$

$$\hat{\psi}(l\omega) = (2\pi)^{-1/2} e^{-(l\omega-\omega_\psi)/2}$$

- Convolved at 81 scales (base-2 logarithmic progression)
- Complex valued wavelet coefficients:

$$\tilde{p}(l,t) = \int p(t')\,\psi^*\left(\frac{t'-t}{l}\right) dt$$



- Energy density / local wavelet power spectrum (WPS) / global WPS:

$$E(l,t) = \frac{|\tilde{p}(l,t)|^2}{l} \qquad E(l,t) \rightarrow E(f,t) \qquad \overline{E} = 1/T \int_T E\,dt$$

[1] Cohen, "*Time-frequency distributions – a review*," Proc. of the IEEE, 77/7, 1989
[2] Farge, "*Wavelet transforms and their application to turbulence*," Ann. Rev. Fluid Mech. 24, 1992
[3] Addison, "*The illustrated wavelet transform handbook*," Taylor & Francis, New York, NY, 2002

Shock Quantification

Wavelet Transform

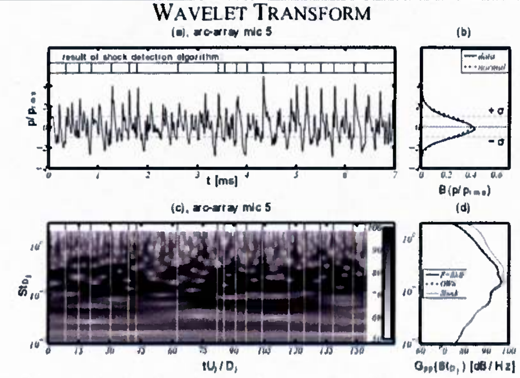


Figure 7. (a) Pressure time series with markings at which shock-structures are detected by the SDA, (b) PDF of the signal, (c) associated WPS, $E(St_{D_j}, t)$ in dB/Hz, p_{ref} = 20 μPa and (d) the GWS, Fourier spectrum and shock spectrum (5% bandwidth moving filter). Note: figures a,c employ identical time ranges but non-dimensional time is indicated in figure c.

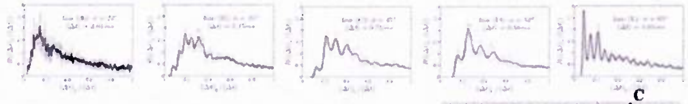
QUANTIFYING CRACKLE – TEMPORAL CHARACTER

1st-order intermittence of shock-structure instances

- $(\Delta t)_i = t_{i+1} - t_i$
- $\langle \Delta t \rangle = \frac{1}{M} \sum_{i=1}^{M} (\Delta t)_i$

PDF's of 1st-order intermittence

- Modal trends near the Mach angle



A

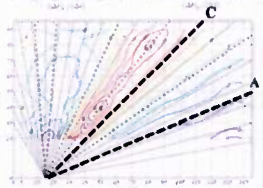
$100s^{-1}$ raw

- $\langle \Delta t \rangle$ = 2.75ms
- S_a = 364s^{-1}
- # shocks = 6k

C

$100s^{-1}$ raw

- $\langle \Delta t \rangle$ = 0.61ms
- S_a = 1,628s^{-1}
- # shocks = 28k



QUANTIFYING CRACKLE – SPECTRAL CHARACTER

Scaling to replicate full-scale

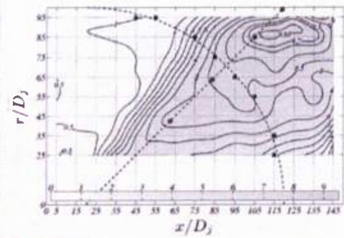
- Ffowcs Williams *et al.* 1975: *"crackle can be scaled"*
- Scaling:

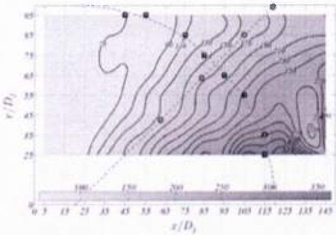
$$St_{D_j} = \frac{fD_j}{U_j} \quad \left.\begin{array}{l} D_j = 1in; U_j = 610m/s \\ D_j = 24in; U_j = 1100m/s \\ (M_j = 1.5, T_j = 1500K) \end{array}\right\} 12:1$$

Energy gain – Krothapalli *et al.* 2000

- GWS$_p$-A → Shock spectrum
- Only function of Θ
- Ffowcs Williams *et al.* 1974: "*…crackle is independent of the distance travelled by the sound…*"

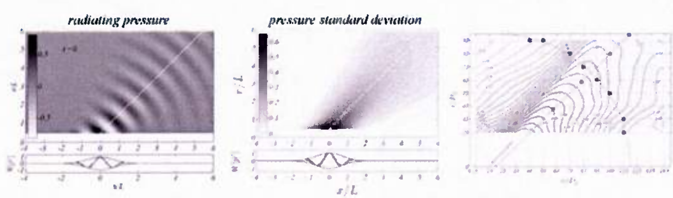
(d), $S(\dot{p})/S(\dot{p})_{max} \times 10$





MACH WAVE EMISSION AND CRACKLE

- Shock properties embedded in the pressure waveform are constant along rays emanating from the post-potential core regions of the flow.
- Wavelet based transform used to quantify spectral properties of the shock structure
  - Increased energy in higher frequency (not surprising…like a delta function!)
- Propose the use of **percent energy gain** as metric for the perception of crackle
  - Instead of skewness … appears shallow angle observer bears the brunt of it all.
- Wavepacket models are resourceful tools that demonstrate a real promise in understanding these mechanisms: Morris (2009), Papamoschou (2011), Kuo et al. (2012), Jordan & Colonius (2013)

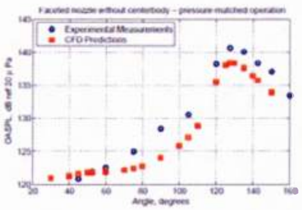


OUTLINE OF DISCUSSION

- Brief discussion of the jet facilities and characteristics:
  - Shock Free Nozzle at UT-Austin
  - Conic-Section Nozzle at U. Mississippi
- What we learned about Mach wave emission and crackle…
- How we improved Hybrid RANS/LES modeling for military style nozzles…
- What we found from the computational phased array analysis…
- What we have learned by investigating noise source terms with LES data…
- How we setup and acquired the synchronous data set…
  - Preliminary results of streak-image analysis.
  - Preliminary results from Time-Resolved PIV analysis.
- Another promising approach… Plenoptic PIV

CFD Simulations Using Hybrid RANS-LES

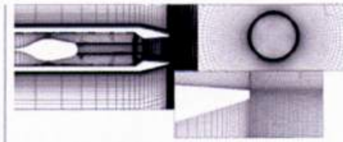
- Zonal versus Hybrid RANS-LES
  - Zonal RANS-LES (typical):
    - RANS solution at nozzle exit used as inflow condition for LES.
    - Under-predicts OASPL levels across all polar angles.
  - Hybrid RANS-LES (HRLES):
    - Internal nozzle geometry included in computational simulations.
    - RANS solution near bounding surfaces.
    - Transitions to LES based on eddy viscosity.
    - Measurable improvement in far-field acoustic results.

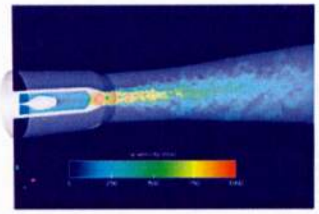


CFD Simulations using HRLES

Methodology

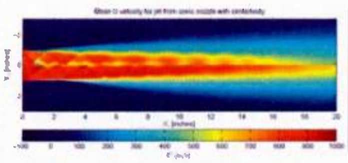
- Flow Computation
  - ≈ 7 million grid points
  - Computational Domain: "Fan Face" to 30 D_j
  - 5^{th} order spatial upwind differencing
  - 4^{th} order temporal Runge-Kutta
  - Parallelized using MPI
- Acoustic Computation
  - 200 kHz data recorded on an acoustic data surface (ADS)
    - CFD time step = 5e-8 seconds
  - Ffowcs-Williams and Hawkings (FW-H) equations used to compute noise at desired farfield location



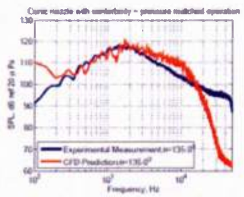


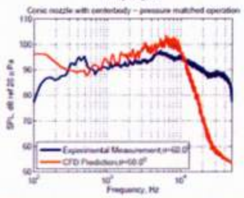
CFD Simulations using Hybrid RANS-LES

Mean and Fluctuating Characteristics



Top: Overexpanded | Bottom: Pressure matched





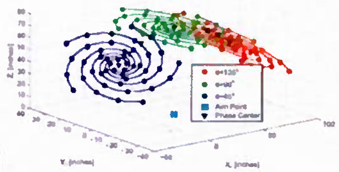
- Exit Boundary Layer
  - Appears initially laminar
- Spectral Characteristics
  - Good agreement out to grid resolution limit of ≈ 10 kHz.

Outline of Discussion

- Brief discussion of the jet facilities and characteristics:
  - Shock Free Nozzle at U. Texas
  - Conic-Section Nozzle at U. Mississippi
- What we learned about Mach wave emission and crackle…
- How we improved Hybrid RANS/LES modeling for military style nozzles…
- **What we found from the computational phased array analysis…**
- What we have learned by investigating noise source terms with LES data…
- How we setup and acquired the synchronous data set…
  - Preliminary results of streak-image analysis
  - Preliminary results from Time-Resolved PIV analysis
- Another promising approach… Plenoptic PIV

Phased Array Calculations

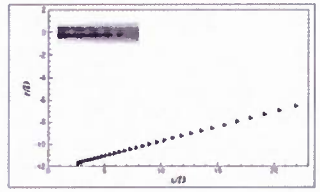
- ADS → F-W&H → Array Mics
  - Possibility to use locations not feasible in a laboratory setting due to spatial or flowfield restrictions.
  - Allows for use of many more microphones than practically feasible in experimental work.
  - Allows for rapidly reconfigurable phased arrays of different designs.
    - Can tailor position/size to frequency/wavenumber/propagation path of interest.
- Caveat:
  - Obtaining "sufficient" ensembles requires numerous time-resolved CFD iterations.
- Application:
  - Use multi-arm spiral arrays with sensor at logarithmically separated spacing.
  - Three arrays oriented at different polar angles to localize sources corresponding to different jet noise components.



Experimental Beamforming

Estimate of Ensemble Requirements

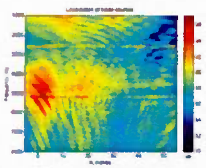
- Data Acquisition:
  - Linear array of logarithmically separated sensors in (x, r)-plane



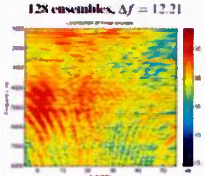
Experimental Beamforming

Estimate of Ensemble Requirements

- Data Acquisition:
  - Linear array of logarithmically separated sensors in (x, r)-plane
- Results of Delay-and-Sum (DAS) Beamforming
  - DAS results refined using DAMAS technique.
- Conclusion
  - At least 6 ensembles at $\Delta f = 48.83$ Hz are required for satisfactory resolution of acoustic sources
    - Corresponds to ≈2.5 million CFD iterations.



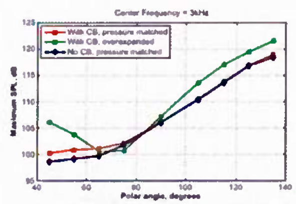
128 ensembles, $\Delta f = 12.21$



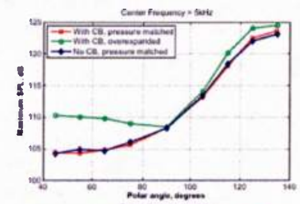
4 ensembles, $\Delta f = 48.83$

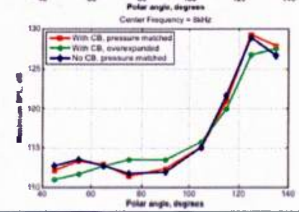
Insights From DAS Beamforming

Overexpanded with Centerbody Hot - CFD



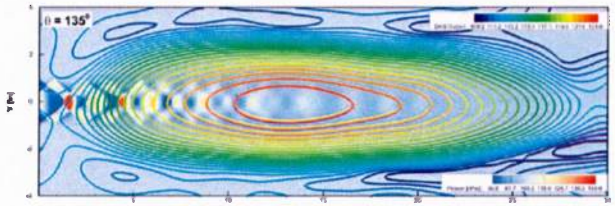
- General directionality follows expectations.
- Centerbody has negligible effect at these NPR's.
- Shock noise clearly present in the overexpanded conditions at the 3.15 kHz and 5 kHz center frequencies.
- At 8 kHz, all three configurations have similar noise levels across all frequencies.





DAS Results, 5 kHz Center Frequency

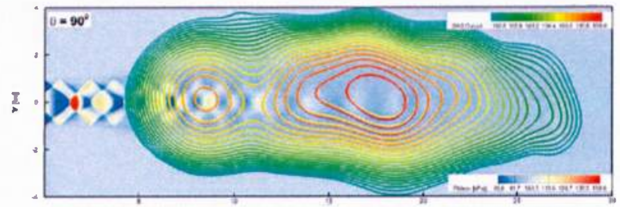
Nozzle with Centerbody, Pressure Matched Operation



- Peak noise (135°): mixing noise appears to peak $\approx 6D_j$
- Sideline (90°)
  - Peak amplitude $\approx 8D_j$.
  - Multiple peaks may be evidence of shock cell locations.
- Upstream (45°): lower amplitude shock noise extends up to $\approx 15D_j$.

DAS Results, 5 kHz Center Frequency

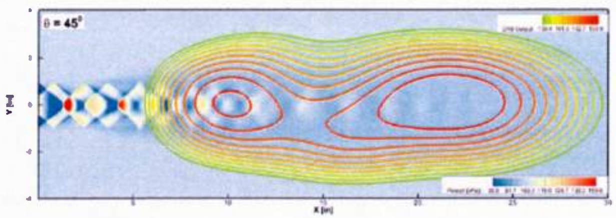
Nozzle with Centerbody, Pressure Matched Operation



- Peak noise (135°): mixing noise appears to peak $\approx 6D_j$
- Sideline (90°)
  - Peak amplitude $\approx 8D_j$.
  - Multiple peaks may be evidence of shock cell locations.
- Upstream (45°): lower amplitude shock noise extends up to $\approx 15D_j$.

DAS Results, 5 kHz Center Frequency

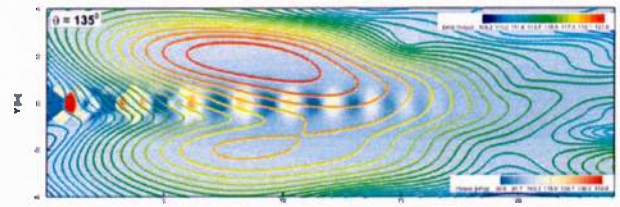
Nozzle with Centerbody, Pressure Matched Operation



- Peak noise (135°): mixing noise appears to peak $\approx 6D_j$
- Sideline (90°)
  - Peak amplitude $\approx 8D_j$.
  - Multiple peaks may be evidence of shock cell locations.
- Upstream (45°): lower amplitude shock noise extends up to $\approx 15D_j$.

DAS Results, 3.15 kHz Center Frequency

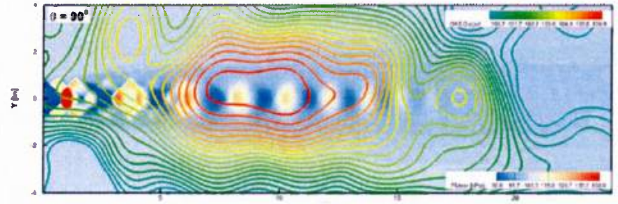
Nozzle with Centerbody, Overexpanded Operation



- Source regions extend only $\approx 8D_j$.
- Shear layer & shock cells seem more significant.
  - Two distinct source locations in the shear layers apparent at 45°.

DAS Results, 3.15 kHz Center Frequency

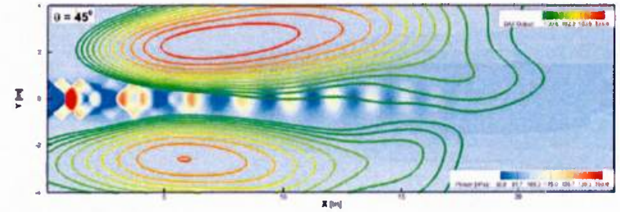
Nozzle with Centerbody, Overexpanded Operation



- Source regions extend only $\approx 8D_j$.
- Shear layer & shock cells seem more significant.
  - Two distinct source locations in the shear layers apparent at 45°.

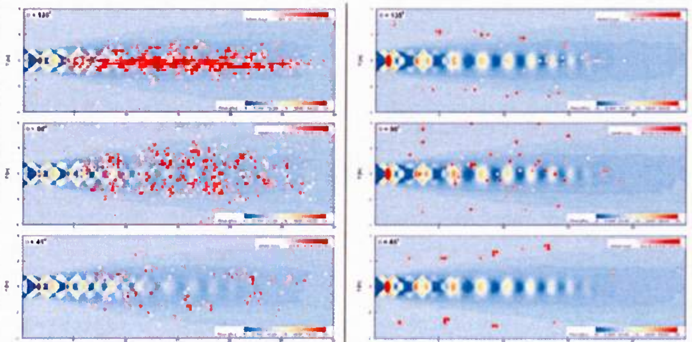
DAS Results, 3.15 kHz Center Frequency

Nozzle with Centerbody, Overexpanded Operation



- Source regions extend only $\approx 8D_j$.
- Shear layer & shock cells seem more significant.
  - Two distinct source locations in the shear layers apparent at 45°.

DAMAS Results, Nozzle with Centerbody



5 kHz Center Frequency, Pressure Matched Operation
Mixing Noise Dominant

3.15 kHz Center Frequency, Overexpanded Operation
Shock Noise Dominant

Outline of Discussion

- Brief discussion of the jet facilities and characteristics:
  - Shock Free Nozzle at UT-Austin
  - Conic-Section Nozzle at U. Mississippi
- What we learned about Mach wave emission and crackle…
- How we improved Hybrid RANS/LES modeling for military style nozzles…
- What we found from the computational phased array analysis…
- **What we have learned by investigating noise source terms with LES data…**
- How we setup and acquired the synchronous data set…
  - Preliminary results of streak-image analysis.
  - Preliminary results from Time-Resolved PIV analysis.
- Another promising approach… Plenoptic PTV

Noise Sources in Supersonic Heated Jets

Challenges: One must resolve both space and time.

- **Experimental handicaps:**
  - Difficult to resolve both space and time (PIV-spatial, LDV-temporal)
  - Limited access to thermophysical properties.
- **Numerical handicaps:**
  - Meshing requirements required for stabile solution (still not possible for DNS at realistic Reynolds numbers).
  - Statistical convergence

Objective / Motivation:

- How we can leverage the strengths of both tools to address outstanding challenges in jet noise?
  - "Lighthill-like" approach (still an analogy!)
    - Effects of viscosity, heat, compressibility, 2-D vs. 3-D
  - Wavenumber frequency make-up inside the source field.

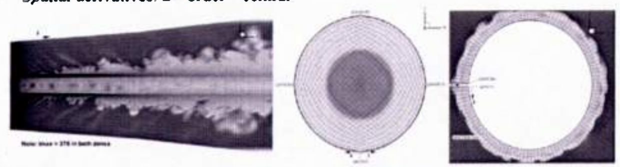
The Large Eddy Simulation

- Fully expanded tactical aircraft nozzle:

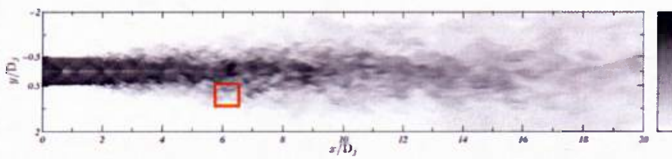
NPR	5.21	$\dot{m}$[kg/s]	0.9578	ρ_j/ρ_∞	0.46
D_j [m]	0.0508	U_j [m/s]	876.6	a_j/a_∞	1.46
T_0 [K]	1005	M_j	1.74	ϕ[deg]	60.55
T_j [K]	643	M_a	2.54		
T_∞ [K]	293	Re_j	830000		

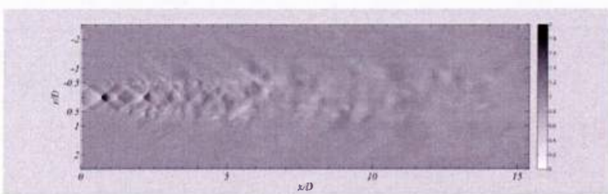
Table 1. Performance properties of the nozzle based on quasi 1-d isentropic compressible flow equations.

- Large Eddy Simulation provided by CRAFT-Tech
  - Ideal Gas Law, Sutherland Law
  - Time Resolved Data Saved at 200 kHz
  - Differencing scheme: 5th order in space, 4th order RK in time.
  - Spatial derivatives: 2nd order – central



The Large Eddy Simulation





Lighthill's Acoustic Analogy

- Inhomogeneous wave equation:

$$\frac{\partial^2 \rho}{\partial t^2} - c_\circ^2 \frac{\partial^2 \rho}{\partial x_i \partial x_i} = \frac{\partial^2 T_{ij}}{\partial x_i \partial x_j}$$

- The Lighthill tensor: $$T_{ij,\nu,\rho,3} = \underbrace{\boxed{\bar{\rho}\tilde{u}_i\tilde{u}_j - \bar{\rho}U_iU_j}}_{(1)} + \underbrace{\boxed{(p' - c_\circ^2\rho')\delta_{ij}}}_{(2)} - \underbrace{\boxed{\tau_{ij}}}_{(3)}$$
- Viscous stress tensor for Stokesian gas:

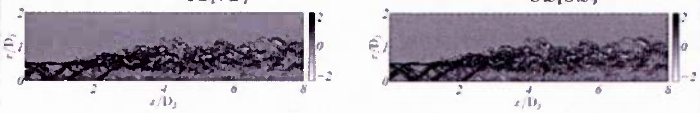
$$\tau_{ij} = \mu\left(-\frac{\partial \tilde{u}_i}{\partial x_j} - \frac{\partial \tilde{u}_j}{\partial x_i} + \frac{2}{3}\left(\frac{\partial \tilde{u}_k}{\partial x_k}\right)\delta_{ij}\right)$$

- How do each of these terms contribute to the acoustic analogy and the generation of sound by jets? –given the restrictions imposed by a time-resolved PIV system.
  - (3) viscous effects?
  - (2) heating effects?
  - (1) 2D versus 3D

$$\boxed{T_{ij,2} = \tilde{u}_i\tilde{u}_j - U_iU_j} \longleftarrow \text{"simple"}$$

Effects of Simplifying Assumptions

$$S_{\nu,\rho,3} = \frac{\partial^2 T_{ij,\nu,\rho,3}}{\partial x_i \partial x_j} \qquad S_{\rho,3} = \frac{\partial^2 T_{ij,\rho,3}}{\partial x_i \partial x_j}$$



$$S_3 = \frac{\partial^2 T_{ij,3}}{\partial x_i \partial x_j} \qquad S_2 = \frac{\partial^2 T_{ij,2}}{\partial x_i \partial x_j}$$

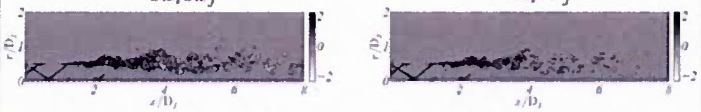


Figure 6. Contours of (a) $S_{\nu,\rho,3}$ (b) $S_{\rho,3}$ (c) S_3 (d) S_2. Amplitudes have been normalized by $\rho_j U_j^2 D_j^{-2}$ and are plotted in logarithmic scale.

Wavenumber Frequency Characteristics

- Separating radiating and evanescent components of the signal.
  - Use wavenumber frequency spectra:

$$S(k_x, f) = \frac{1}{2\pi} \iint S(x,t) W(x) e^{-i(k_x x + 2\pi f t)}\, dx dt$$

  - Need to define a threshold for filtering!!
    - Temperature variations effect variations in the sound speed.
    - What sound speed do we use?
      - That of the ambient field or that of the gas where the source term lies?

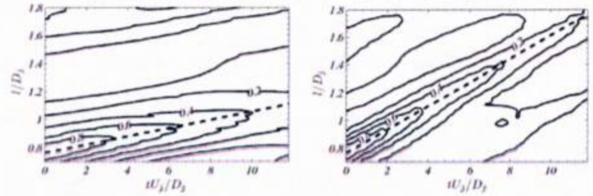


Figure 8. Typical space-time contours for the streamwise velocity along a line in the flow where (a) $U_c = a_\infty$ and (b) $U_c = 0.8U_j$. The dashed line identifies the local convective speed.

Radial Collapse of Jet Properties

- Normalization: $r^* = (r - r_{50})/(r_{90} - r_{10})$
- Source Convective Speeds:
  - Faster than the mean on the Low-Speed Side
  - Slower than the mean on the High-Speed Side
- Horizontal Lines: $U_c = a_\infty$, $U_c = 0.7U_j$, and $U_c = 0.8U_j$

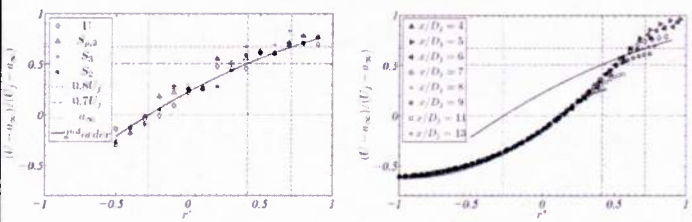


Figure 9. (a) Radial distribution of the convective velocity obtained from two-point correlations. (b) Collapse of the mean streamwise velocity overlaid the average convective velocity.

Wavenumber/Frequency – Effect of Simplification

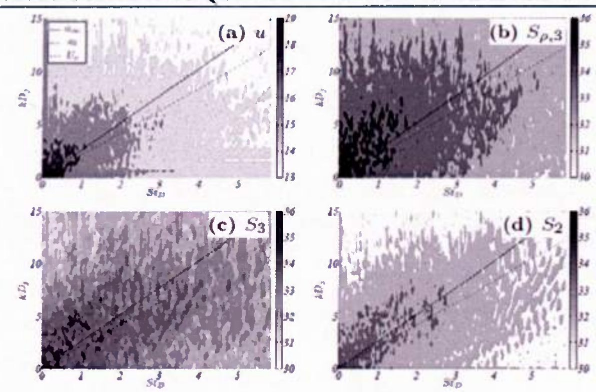


Figure 10. Wave-number frequency contours of (a) u (b) $S_{\rho,3}$ (c) S_3 (d) S_2 along the line where $U_c = a_\infty$ in a logarithmic scale.

Region of Acoustic Efficiency

- Percentage of Acoustical Efficiency: ratio of …
  - Total Spectral Energy (positive k_x, f): E_t
  - Acoustically Efficient Energy (sonic threshold): E_s
- Highest Variance in Velocity: Near Center of Shear Layer
- Highest Efficiency Percentage: On High-Speed Side

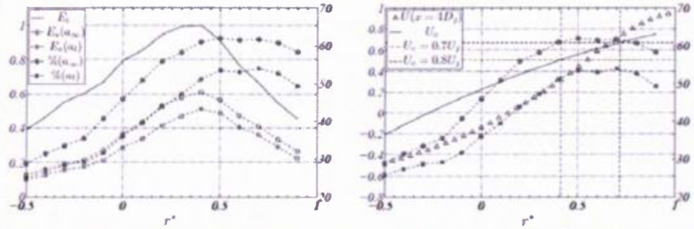


Figure 12. Total and supersonic spectral energy levels for two different sound-speeds of reference giving the percentages of acoustic efficiency (a) with the convective speeds and the mean velocity radial profile (b) along the 15 arrays. The right y-axis gives the percentage values while the left y-axis gives the spectral energy level normalized by its maximum in (a) and $(U - a_\infty)/(U_j - a_\infty)$ in (b).

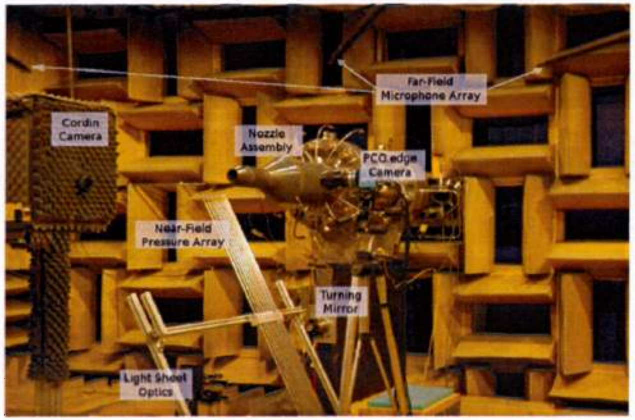
Present Observations from CFD Data Analysis

- In wavenumber/frequency space it appears that the simplifications imposed by the experiment may not be completely limiting.
- LES confirmed negligible effect of viscous term on acoustic analogy (Freund 2003).
- Present analysis firmly sets the stage for investigating the wavenumber/frequency spectra using the time-resolved PIV data recently acquired.

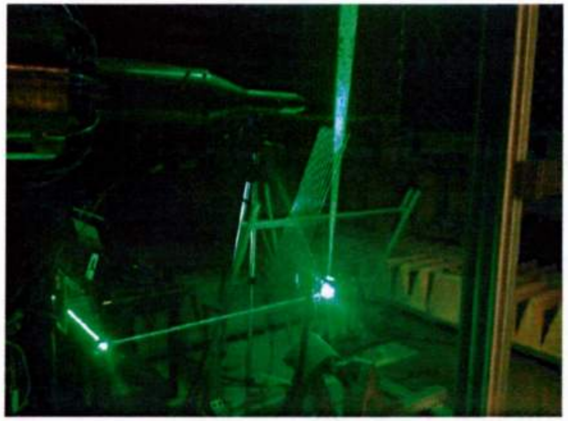
Outline of Discussion

- Brief discussion of the jet facilities and characteristics:
  - Shock Free Nozzle at UT-Austin
  - Conic-Section Nozzle at U. Mississippi
- What we learned about Mach wave emission and crackle…
- How we improved Hybrid RANS/LES modeling for military style nozzles…
- What we found from the computational phased array analysis
- What we have learned by investigating noise source terms with LES data…
- How we setup and acquired the synchronous data set…
  - Preliminary results of streak-image analysis
  - Preliminary results from Time-Resolved PIV analysis
- Another promising approach… Plenoptic PIV

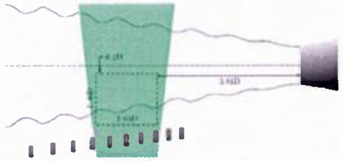
Setup Details and Run Conditions



Setup Details and Run Conditions



Setup Details and Run Conditions

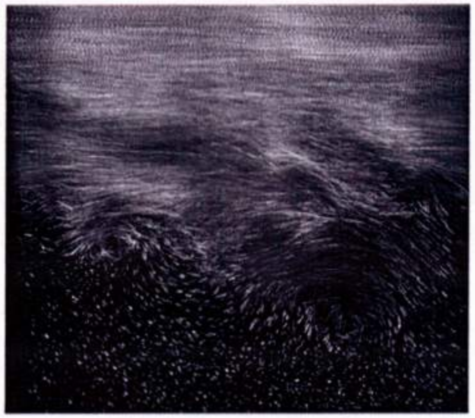


- Conic without Centerbody, Overexpanded
- $NPR = 3.93$, $M_j = 1.555$, $T_j = 1350\,^{\circ}\mathrm{F}$, $M_a = 2.34$
- Cordin Acquisition:
  - 303, 16-image acquisition ($\approx$ 1 every 15 sec.)
  - 1 μs framing rate (15 μs total time)
- PCO.Edge Acquisition
  - Image-Pair (typical PIV method) acquired every 0.5 seconds
  - First Frame – Single Exposure
  - Second Frame – Multi-Exposure

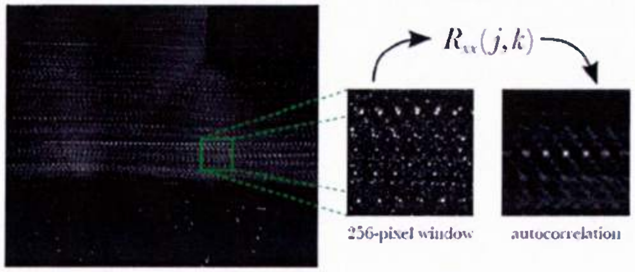
Outline of Discussion

- Brief discussion of the jet facilities and characteristics:
  - Shock Free Nozzle at UT-Austin
  - Conic-Section Nozzle at U. Mississippi
- What we learned about Mach wave emission and crackle...
- How we improved Hybrid RANS/LES modeling for military style nozzles...
- What we found from the computational phased array analysis...
- What we have learned by investigating noise source terms with LES data...
- How we setup and acquired the synchronous data set...
  - **Preliminary results of streak-image analysis.**
  - Preliminary results from Time-Resolved PIV analysis.
- Another promising approach... Plenoptic PIV

Streak-Images Reveal Coherent Structure

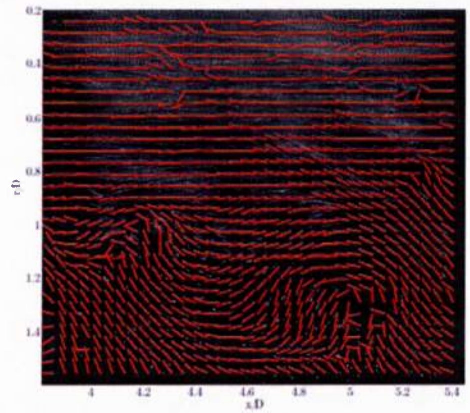


Streak-Image Analysis



- Application of windowed autocorrelation methods.
- Identifies direction and velocity magnitude.

Streak-Images Reveal Coherent Structure



Outline of Discussion

- Brief discussion of the jet facilities and characteristics
  - Shock Free Nozzle at UT-Austin
  - Conic-Section Nozzle at U. Mississippi
- What we learned about Mach wave emission and crackle…
- How we improved Hybrid RANS/LES modeling for military style nozzles…
- What we found from the computational phased array analysis…
- What we have learned by investigating noise source terms with LES data…
- How we setup and acquired the synchronous data set…
  - Preliminary results of streak-image analysis.
  - Preliminary results from Time-Resolved PIV analysis.
- Another promising approach… Plenoptic PIV

MHz Rate PIV

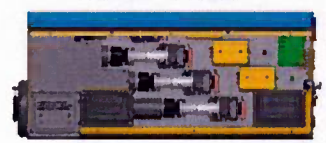
Development & Implementation

- Utilize a MHz rate *pulse burst laser system* and MHz rate *camera* to acquire a sequence of particle images at high speeds
- Determine velocity using PIV cross-correlation algorithms

- Transport equipment form AU to NCPA
- Facility integration issues
- Development of robust image processing algorithms suited for MHz rate image data

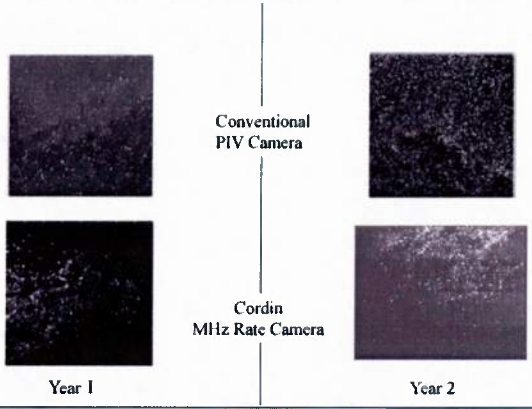
Pulse Burst Laser System

Cordin 222-4G Camera



MHz Rate PIV

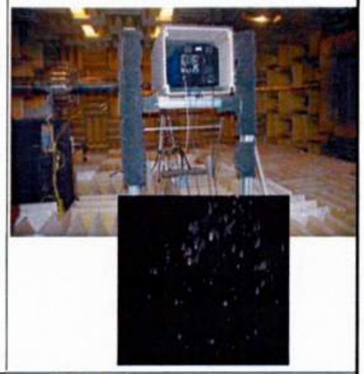
Challenge: Particle Seeding & Image Quality



MHz Rate PIV

Challenge: Intense Acoustic Environment

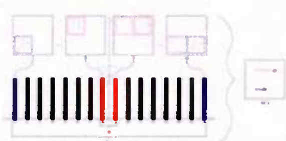
- Pellicle beam splitters used to split the image along separate paths have a resonant frequency in same range as acoustic frequencies produced by jet
- Led to *image blurring* due to vibrating beam splitter
- Solution
  - Construction of anechoic chamber for the camera
  - Move camera further back from flow field

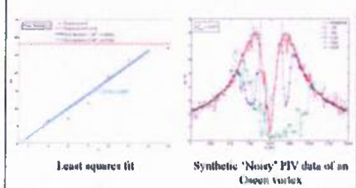


MHz Rate PIV

Dynamic Evaluation via Ordinary Least Squares (DEVOLS)

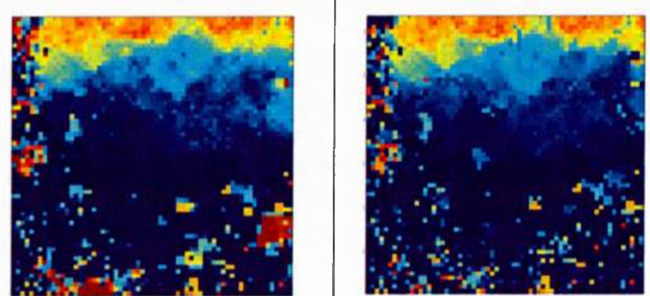
- MHz rate camera image quality compromised by particle seed density, laser power, intensifier and beamsplitters
- Algorithm developed to provide
  - *Robust* velocity measurements
  - Increased dynamic range
- DEVOLS
  - Utilizes multiple image pairs centered around an instant in time to optimally determine local velocity
  - Least squares fit of displacement vs. time





MHz Rate PIV

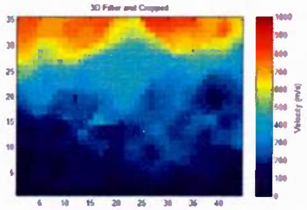
Preliminary Results: DEVOLS Algorithm



MHz Rate PIV

Preliminary Results

- Streamwise component of velocity
- Standard PIV
- Low-pass filtered in space and time
- Cropped to region with highest signal levels
- Data reduction is time-consuming process and is ongoing



MHz Rate PIV

Future Work: Better Camera Technology

- Cordin - 222-4G
  - Best available ~2 years ago
  - **16 frames** @ 2,048 x 2,048 pixel resolution
  - Pellicle Beamsplitters - frame-to-frame jitter, reduced signal, susceptible to vibrations
  - Intensifier – high-speed gating, decreased spatial resolution and image quality
- Specialised Imaging - Kirana
  - **180 frames** @ 924 x 768 pixel resolution
  - Improved image quality
  - Custom image sensor with on-chip memory (no beamsplitters = greater sensitivity and no frame-to-frame alignment issues)
  - Available for demo in next few months

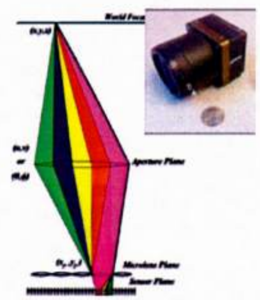
Outline of Discussion

- Brief discussion of the jet facilities and characteristics:
  - Shock Free Nozzle at UT-Austin
  - Conic-Section Nozzle at U. Mississippi
- What we learned about Mach wave emission and crackle…
- How we improved Hybrid RANS/LES modeling for military style nozzles…
- What we found from the computational phased array analysis…
- What we have learned by investigating noise source terms with LES data…
- How we setup and acquired the synchronous data set…
  - Preliminary results of streak-image analysis
  - Preliminary results from Time-Resolved PIV analysis
- Another promising approach… Plenoptic PIV

Volumetric PIV

Light-Field Imaging and the Plenoptic Camera

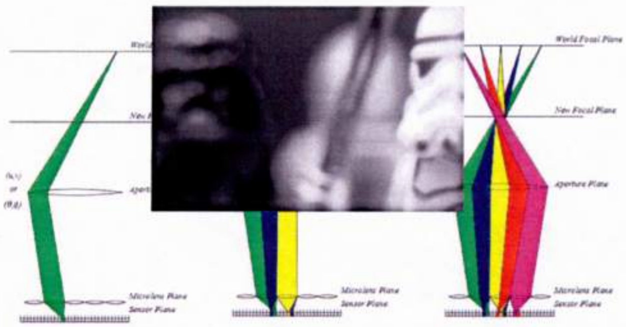
- Analysis of planar data often must assume axisymmetric or helical-type flow structures
- Volumetric PIV
  - Tomo-PIV – Multiple cameras
  - Generally limited to thin volumes (10 mm or less)
- Light-field imaging
  - Considers the complete distribution of light in space
  - Record both the position and angle of light rays traversing a volume
- Plenoptic camera
  - Utilizes a microlens array to record the light-field
  - Small, compact, robust



Plenoptic Camera

VOLUMETRIC PIV

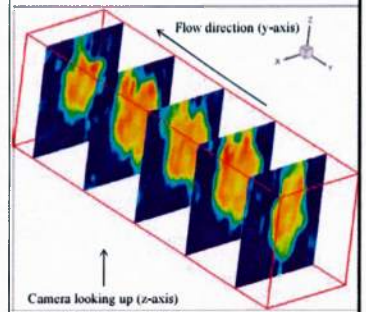
COMPUTATIONAL REFOCUSING WITH A PLENOPTIC CAMERA



VOLUMETRIC PIV

PLENOPTIC PIV: PRELIMINARY RESULTS

- Tomographic reconstruction + 3D cross-correlation algorithm
- Proof-of-concept at NCPA
  - Volume size: 60.7 mm x 90.9 mm x 100 mm
  - Centered approximately at x/d = 1.5
- *1st ever volumetric PIV measurement* in a supersonic jet at this Reynolds number
- *Single day* of experiments
  - Did not optimize illumination, particle seeding, tomography parameters, etc.
  - Quite pleased with results considering this was 1st attempt



Color corresponds to streamwise velocity

SUMMARY

- What we learned about Mach wave emission and crackle…
- How we improved Hybrid RANS/LES modeling for military style nozzles…
- What we found from the computational phased array analysis…
- What we have learned by investigating noise source terms with LES data…
- Strong preliminary results from Time-Resolved PIV analysis…
- Exciting advancements in experimental techniques…

PLANS FOR YEAR 3

- Reduce synchronized data set to ensembles of time dependent velocity and pressure for further analysis.
  - Apply coupled wavenumber/frequency analysis.
  - Make available to other BRC teams as appropriate
- Modal decomposition of velocity data retaining short-time evolution as a dependent variable: $u_i(x,y,\tau) = \sum_s \alpha^{(s)} \phi_i^{(s)}(x,y,\tau)$
- Run additional CFD iterations to further enhance computational database for beam-forming analysis.
  - Use results for 3-space wavenumber/frequency analysis.
- Perform synchronized data acquisition with Kirana camera
  - No later than Fall 2013 to give time for analysis prior to end of program.
- Continue analysis of Plenoptic PIV data: Source identification?
- Use shock detection algorithm with stochastic estimation to identify associated flow-field structures.

PUBLICATIONS

[1] BAARS, W. J., TINNEY, C. E., MURRAY, N. E., JANSEN, B. J. & PANICKAR, P. (2011) "The Effect of Heat on Turbulent Mixing Noise in Supersonic Jets," in *49th AIAA Aerospace Sciences Meeting*, Paper 2011-1029 (Orlando, FL).

[2] BAARS, W. J., TINNEY, C. E. & WOCHNER, M. S. (2012) "Nonlinear Noise Propagation from a Fully Expanded Mach 3 Jet," in *50th AIAA Aerospace Science Meeting*, Paper 2012-1177 (Nashville, TN).

[3] MURRAY, N. E., LYONS, G. W., TINNEY, C. E., DONALD, B., BAARS, W. J., THUROW, B. S., HAYNES, R. H. & PANICKAR, P. (2012) "A Laboratory Framework for Synchronous Near/Far-Field Acoustics and MHz PIV in High-Temperature, Shock-Containing, Jets," in *Proceedings of the Internoise 2012/ASME NCAD Meeting*, ASME/NCAD-1270 [invited] (New York City, NY).

[4] BAARS, W. J. & TINNEY, C. E. (2012) "Scaling Model for Nonlinear Supersonic Jet Noise," in *Bulletin of the American Physical Society*, 57:17, Abstract D24.8 (San Diego, CA).

[5] HAYNES, R. H., BROCK, B. A. & THUROW, B. S. (2013) "Application of MHz Frame Rate, High Dynamic Range PIV to a High-Temperature, Shock-Containing Jet," in *51st AIAA Aerospace Sciences Meeting*, 2013-0774 (Grapevine, TX).

[6] PANICKAR, P., ERWIN, J., SINHA, N., MURRAY, N. E. & LYONS, G. W. (2013) "Localization of Acoustic Sources in Shock-Containing Jet Flows Using Phased Array Measurements," in *51st AIAA Aerospace Sciences Meeting*, 2013-0613 (Grapevine, TX).

[7] FIÉVET, R., TINNEY, C. E., MURRAY, N. E., LYONS, G. W. & PANICKAR, P. (2013) "Acoustic Source Indicators using LES in a Fully Expanded and Heated Supersonic Jet," in *19th AIAA/CEAS Aeroacoustics Conference*, Paper 2013-2193 (Berlin, Germany).

[8] BAARS, W. J. & TINNEY, C. E. (2013) "Quantifying crackle-inducing acoustic shock-structures emitted by a fully-expanded Mach 3 jet," in *19th AIAA/CEAS Aeroacoustics Conference*, Paper 2013-2081 (Berlin, Germany).

[9] BAARS, W. J. & TINNEY, C. E. (2013) "A Temporal and Spectral Quantification of the Crackle Component in Supersonic Jet Noise," in *2nd Symposium on Fluid-Structure-Sound Interactions and Control*, p. 170.

[10] BAARS, W. J. (2013) *Acoustics from High-Speed Jets with Crackle*, Ph.D. Dissertation, The University of Texas at Austin.

[11] BAARS, W. J., TINNEY, C. E. & WOCHNER, M. S. "Nonlinear Distortion of Acoustic Waveforms from High-Speed Jets," *Journal of Fluid Mechanics*, [in review].

CATALOG OF RUN CONDITIONS

[illegible]

CATALOG OF RUN CONDITIONS

[illegible]

CATALOG OF RUN CONDITIONS

[illegible]